Fission Technology for Exploring and Utilizing the Solar System

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Abstract. Fission technology can enable rapid, affordable access to any point in the solar system. Potential fission-based transportation options include bimodal nuclear thermal rockets, high specific energy propulsion systems, and pulsed fission propulsion systems. In-space propellant re-supply enhances the effective performance of all systems, but requires significant infrastructure development. Safe, timely, affordable utilization of first-generation space fission propulsion systems will enable the development of more advanced systems. First generation space systems will build on over 45 years of US and international space fission system technology development to minimize cost.

INTRODUCTION

Fission technology can enable rapid, affordable access to any point in the solar system. Advanced concepts (i.e. the "Medusa" concept (Solem, 1993) and vapor or droplet core fission systems driving high-efficiency thrusters (Anghaie, 1999)) could reduce trip time to Mars, Jupiter, and beyond by an order of magnitude compared to today's systems. In the mid-term, bimodal nuclear thermal rockets with liquid oxygen afterburners (LANTR) could reduce earth-lunar transit time to 24 hours, enable affordable six-month transits to Mars, and explore much of the inner solar system utilizing in-situ propellant re-supply (Borowski, 1999). In-space propellant re-supply could greatly enhance the effective performance of all propulsion systems.

Compared to other advanced propulsion options, fission systems are conceptually quite simple. All that is required is for the right materials to be placed in the right geometry - no extreme temperatures or pressures required - and the system will operate. In addition, the fuel for fission systems (highly enriched uranium) is virtually non-radioactive, containing 0.064 curies/kg. This compares quite favorably to radioisotope systems (Pu-238 contains 17,000 curies/kg) and D-T fusion systems (tritium contains 10,000,000 curies/kg). At launch, a typical space fission propulsion system would contain an order of magnitude lower onboard radioactivity than Mars Pathfinder's Sojourner Rover. The primary safety issue with fission systems is avoiding inadvertent system start – addressing this issue through proper system design is quite straightforward. The energy density of fission is higher than that of D-D fusion and higher than the charged particle energy density of D-T fusion. The potential capability of fission propulsion systems is compared with that of chemical propulsion systems and fusion propulsion systems in Table 1.

Table 1. Comparison of Fission Propulsion to Chemical and Fusion Propulsion.

Parameter	Chemical	D-D Fusion	D-T Fusion	Fission

Theoretical Fuel Energy Density				
Demonstrated Fuel Energy Density				
Charged Particle Energy Density				
Neutron Energy (Potential Radiation Damage)				
Demonstrated Engineering Q (Total Energy Balance)				
Fuel Cost				
Fuel Availability				
Fuel Heat Generation During Storage				
Radioactivity at Launch				

The potential of space fission systems is further illustrated in Figure 1. As shown in the Figure, the energy density in fission systems is seven orders of magnitude greater than that of the best chemical systems. Put another way, completely fissioning a piece of uranium the size of a coke can would yield 50 times more energy than burning all of the chemical fuel contained in the space shuttle main tank. If properly harnessed, the energy density in fissile fuel far exceeds that required to enable rapid access to any point in the solar system. Additionally, the technology readiness level (TRL) of space fission systems is much higher than that of nuclear fusion, matter annihilation, and hot isomeric transition. Fission systems are the nearest-term option for high efficiency, high thrust in-space propulsion.

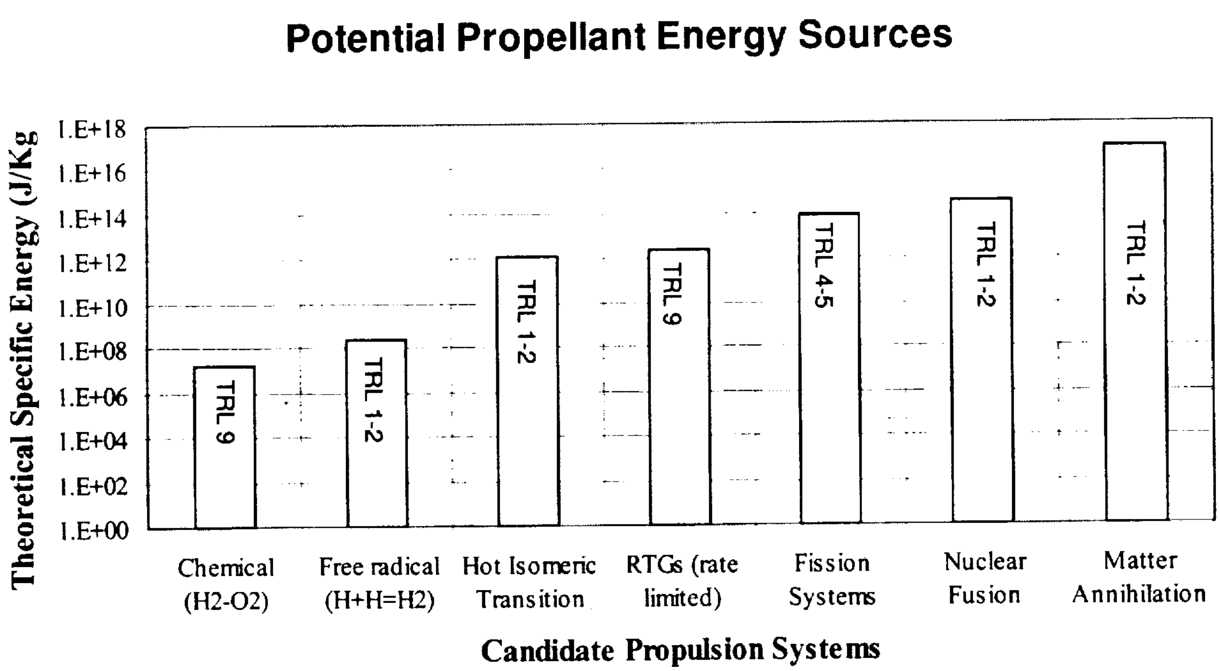

FIGURE 1. Energy density of candidate propellant energy sources.

FIRST GENERATION SPACE FISSION SYSTEMS

Despite the relative simplicity and tremendous potential of space fission systems, the development and utilization of these systems has proven elusive. The first use of fission technology in space occurred 3 April 1965 with the US launch of the SNAP-10A reactor. There have been no additional US uses of space fission systems. While space fission systems were used extensively by the former Soviet Union, their application was limited to earth-orbital missions. Early space fission systems must be safely and affordably utilized if we are to reap the benefits of advanced space fission systems.

Table 2 gives a partial list of major US space fission programs that have failed to result in flight of a system. There are a variety of reasons why these programs failed to result in a flight. The fact that so many programs have failed indicates that a significantly different approach must be taken if future programs are to succeed.

Terrestrial fission systems have been utilized by the government, universities, industry, and utilities for over 50 years. In addition, technology development directly related to space fission systems has been progressing for over 40 years. The next generation fission system should capitalize on this experience. Nuclear testing can be one of the most expensive and time consuming aspects of space fission system development. If a system can be designed to operate within established fuel burnup and component radiation damage limits, the requirement for nuclear testing can be minimized. Designing the system such that resistance heaters can be used to closely simulate heat from fission will also facilitate development and allow extensive testing of the actual flight unit.

Additional innovative approaches will have to be used to ensure that the next space fission system development program results in system utilization. Safety must be the primary focus of the program, but cost and schedule must also be significant drivers. System performance must be adequate, but the desire to make performance more than adequate should not be allowed to drive system cost and schedule. The next generation space fission system must be safe, simple, and as inexpensive to develop and utilize as possible.

To enable utilization of fission systems, a phased approach has been devised.

TABLE 2. Partial list of major US Space Fission Programs that Have Failed to Result in Flight of a System.

• Solid-Core Nuclear Rocket Program • Medium-Power Reactor Experiment (MPRE) • Thermionic Technology Program (1963-1973) • Space Nuclear Thermal Rocket Program • SP-100	• SNAP-50 / SPUR • High-Temperature Gas-Cooled Electric Power Reactor (710 Reactor) • SPAR / SP-100 • Flight Topaz • DOE 40 kWe Thermionic Reactor Program	• Advanced Liquid Metal Cooled Reactor • Advanced Space Nuclear Power Program (SPR) • Multi-Megawatt Program • Thermionic Fuel Element Verification Program • Air Force Bimodal Study

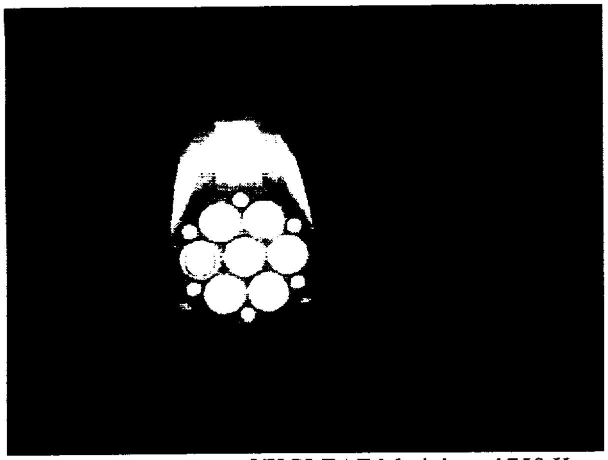

FIGURE 2. Portion of FIGLEAF Module at 1750 K.

FIGURE 3. FIGLEAF Module.

PULSED FISSION (OR FISSION/FUSION) PROPULSION SYSTEMS

Pulsed propulsion systems have been under consideration since the late 1940's. In a pulsed propulsion system, fission or fission/fusion pulses that release between 10^{13} and 10^{15} Joules of energy are used to propel a vehicle. The primary difficulty with pulsed propulsion systems is coupling the pulse to the vehicle without exceeding limits on acceleration. If adequate coupling schemes are devised, effective specific impulses exceeding 50,000 seconds with vehicle thrust-to-weight ratios exceeding 1.0 are feasible. Nearer-term systems would be more likely to have specific impulses on the order of 4000 s, still nearly an order of magnitude greater than the best chemical propulsion systems (Dyson, 1999).

In the energy range of interest, the equivalent specific impulse of pulsed propulsion systems increases with the magnitude of the pulse. The primary obstacle to the utilization of large pulses is devising a method for spreading the acceleration out over a period of several seconds. Large pulses could deliver total impulses on the order of 10^8 kg-m/s or more. Assuming a 200 MT vehicle and a maximum acceleration limit of 250 m/s^2 thus requires that the impulse be delivered to the spacecraft over a minimum of two seconds. Another concern is the cost of the pulse unit. Because cost is not strongly dependent on pulse unit size, the use of large pulses may also result in less expensive missions. A 10^{14} J pulse requires the fissioning of roughly 1.25 kg of uranium. Future research related to pulsed propulsion systems should focus on methods for utilizing large pulses, on the order of 10^{14} J or higher. Systems utilizing large pulses could enable rapid access to any point in the solar system.

Most previous work related to pulsed fission propulsion systems focused on earth-to-orbit systems. This focus drove vehicle designs to those capable of utilizing a rapid series of pulses, on the order of one pulse per second. A system requiring several minutes to reconfigure between pulses may be acceptable for in-space transfer applications. Dealing with variability in pulse sizes and the occasional failure of a pulse unit may also be simplified for in-space transfer applications.

HIGH SPECIFIC ENERGY FISSION PROPULSION SYSTEMS

The specific energy of fissile fuel is $8\text{x}10^{13}$ J/kg. For systems requiring a year of operation at full thrust without refueling, the minimum theoretical specific mass is thus $4\text{x}10^{-4}$ kg/kW. In an actual system, structure, heat removal, energy conversion, waste heat rejection, radiation shielding, and other subsystems will significantly increase specific mass. However, it may still be possible to devise high efficiency (Isp > 3000 s) fission propulsion systems with a specific mass in the 0.1 to 1.0 kg/kW$_{propellant}$ range. Such systems would enable rapid access to any point in the solar system.

Initial research on these systems could involve non-nuclear simulations of vapor or droplet core fission reactors. Advanced energy conversion subsystems including MHD energy conversion and high-temperature Brayton cycles could be investigated. Flowing UF_4 (or other fuel-form) loops could be constructed (using natural or depleted uranium) to validate thermal hydraulic predictions and investigate high temperature materials compatibility.

RECOMMENDATIONS FOR FUTURE RESEARCH

Research should continue on a first generation fission propellant energy source. The focus of this research should be on demonstrating that fission propulsion systems can be developed and utilized in a safe, timely, and affordable fashion. Research on pulsed propulsion systems should focus on methods for utilizing large (1×10^{14} J or greater) pulses. Research on high specific energy systems can be focused in a variety of areas, but should lead to systems capable of providing on the order of a kilowatt of power into the propellant for every kilogram of system mass. Research related to in-situ propellant re-supply can also be focused in a variety of areas, but should lead to the capability to place propellant re-supply stations where they are most needed for a given mission. Research needs related to the LANTR system are detailed elsewhere (Borowski, 1999).

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